Technical Memorandum No. 33-133

Lunar Communications

Eberhardt Rechtin

jpl

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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CONTENTS

TABLES

FIGURES

ABSTRACT

14540

Lunar communication is treated as a problem in physics and practical engineering. Examples are given of communication designs to and from the Earth from both the near and far sides of the Moon and of communications from one point on the Moon's surface to another. The choice of modulation system is shown to depend on the signal-to-noise ratio in a 1-cycle band, the threshold characteristics of the receivers, and the allowable radio-frequency bandwidth. A brief comparison between radio and optical communications shows that radio is more advantageous at present. The Report ends with a set of conclusions.

I. FUNDAMENTALS [1]

Communications to and from the Moon can now be regarded as straightforward engineering, albeit using techniques only recently available. Among these new techniques are large precision antennas, maser amplifiers, coherent transmitters and receivers of high stability, modulation systems of some sophistication, and a worldwide network of stations capable of continuous contact with the Moon.

The final measure of communication system performance is the ratio of signal power to noise power at the receiver output. The received signal power S_{RF} is proportional to the transmitter power, to the effective areas or directivity (gain) of the antennas, and to the inverse square of the communication distance.

[1] This Memorandum is based on a lecture by the author to the University of California at Los Angeles (April 22-25, 1963).

Expressed in equation form:

$$S_{RF} = \frac{P_T \, G_T \, A_R}{4\pi R^2}$$

$$= \frac{P_T \, G_T \, G_R \, \lambda^2}{(4\pi R)^2} \tag{1}$$

where

P_T = the transmitted power

G_T = the transmitting antenna gain

G_R = the receiving antenna gain, also computable as $4\pi/\lambda^2$ times the receiving antenna area A_R

λ = the wavelength of the signal carrier

R = the communication distance in the same units as λ

and

$\lambda^2/(4\pi R)^2$ = the space loss (so *defined* for this discussion)

Spacecraft transmitter powers depend primarily on the size and weight of the spacecraft and its power supply. The state-of-the-art and convenience result in powers of about 10 w in 1963 and of 10 to 50 w by 1968. With the advent of nuclear power sources in spacecraft, transmitter powers of kilowatts might be expected. Transmitter powers for ground transmitters can conveniently be made so large that the usual design practice is to use the large ground powers to simplify the spacecraft receiving system.

Antenna size is limited by cost and achievable precision for ground antennas and by weight and awkwardness for spacecraft antennas. For our purposes here, we will assume that sufficiently economical and precise ground antennas can be constructed of 85-ft diameter in 1963 and of 210-ft diameter by 1968. A tractable size for a spacecraft antenna is a diameter of about 4 ft.

Antenna directivity is selected by considering several factors. For most efficient communications, beamwidths should be small in order to concentrate transmitted power into a small cone; however, small beamwidths demand large antennas of great precision operating at relatively high frequencies. Small beamwidths are also difficult to use operationally: pointing is difficult; signals are difficult to locate in space; the spacecraft attitude-control system must be operating properly. The resultant beamwidth adopted for ground antennas is thus a fraction of a degree. For spacecraft antennas, a dual compromise results in using one beamwidth of about 5 deg (an efficient, directive antenna pattern) and another beamwidth of almost 360 deg (an inefficient, but essentially attitude-independent, antenna pattern).

The received noise power includes contributions from the surroundings and, to a lesser degree, from the communication equipment itself. Communication receivers can now be made so quiet that it is possible to hear radio noise from stars in the sky. Indeed, this is the essence of modern astronomy. It is also possible to hear the rattling of oxygen and water molecules in our atmosphere and the radio radiations from the surface of the Moon and the Earth. Each noise source is characteristically different in its dependence on frequency, direction from the receiver, and angular size in the receiver surroundings.

Before continuing with the discussion of noise, it is worthwhile to define a few terms. It is convenient and physically meaningful to describe noise power in terms of bandwidth, temperature, and spectral density. It can be shown, for bandwidths and radio frequencies of interest, that

$$N_{\mathrm{RF}} \simeq \Phi\, B_{\mathrm{RF}} = kTB_{\mathrm{RF}} \tag{2}$$

where

N_{RF} = noise power in watts

Φ = the noise spectral density in watts per cycle per second

B_{RF} = the radio-frequency bandwidth in cycles per second

k = Boltzman's constant (1.38×10^{-23} w/cps/°K)

and

T = temperature in degrees Kelvin

Noise power (and, consequently, spectral density and temperature) contributions add linearly.

A well-made maser receiving system will produce a noise temperature of between 5 and 10°K. However, such systems are quite difficult to construct because of the need for exceptional care in the fabrication of associated microwave hardware and feeds. At the present time, field operational noise temperatures of maser receiving systems are typically 25 to 30°K. The temperature contributions of the cosmos and of oxygen and rainfall in the atmosphere are functions of frequency (Fig. 1). It can be seen that cosmic noise drops rapidly with increasing frequency whereas atmospheric noise climbs rapidly with frequency. These noise sources act strongly to restrict the choice of frequency for ultrasensitive communications in the region of 1 to 3 Gc/s (1 Gc/s is 10^9 cps). The noise contribution from the surface of the Earth at a temperature of 300°K is sharply reduced by using directive receiving antennas whose sidelobes in the ground direction are made as low gain as possible. By careful antenna design, restriction of the minimum elevation angle of the antenna to about 5 deg above the horizon, and use of beamwidths of a fraction of a degree, the noise-temperature contribution from the surface of the Earth can be kept at about 10°K.

Unfortunately for lunar communications, the noise contribution from the Moon at a temperature of 150 to 250°K (depending upon frequency and Sun illumination) cannot be reduced by not looking at the Moon! However, the small angular size of the Moon (0.5 deg across) is of such help that the noise-temperature contribution can be kept at about 75 to 100°K.

By considering the state-of-the-art in receivers and antennas and by selecting a frequency between 1 to 3 Gc/s, the over-all noise temperature of an Earth receiving station for lunar communications in 1963 is about 200°K and in 1968 should be about 150°K.

With these tools and limitations, communication links between the Moon and the Earth can now be designed.

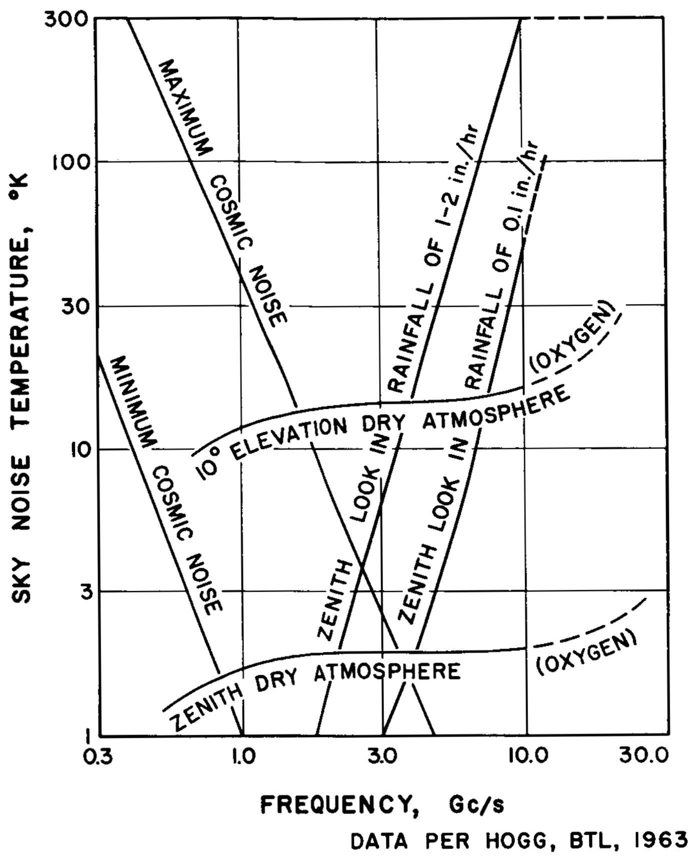

Fig. 1. Sky noise vs. frequency

II. COMMUNICATIONS BETWEEN THE MOON AND THE EARTH

Television promises to be one of the most effective aids in lunar exploration. It also requires the greatest communication capacity, exceeding by orders of magnitude that required for either telemetry or voice. Because television demands the best in the communication art and illustrates some interesting characteristics of modulation systems, it will be considered first.

Table 1 shows an illustrative Moon-to-Earth television link. For reasons discussed previously, the radio frequency (RF) has been chosen at 2.295 Gc/s, the transmitter power at 10 to 50 w, the spacecraft-antenna diameter at 4 ft, the ground-antenna diameter at 85 and 210 ft, and the effective noise temperature at 200 and 150°K. Space loss is the attenuation in decibels suffered by a signal going the distance from an omnidirectional transmitter on the Moon to an omnidirectional receiving antenna on the surface of the Earth. Expressed in decibels, the space loss increases 6 db for every doubling of the distance or radio frequency. Equipment RF losses represent attenuation of the RF energy as it passes through all of the required cables, waveguides, rotary joints, feed apertures, etc. These losses can be reduced by shortening the lengths of the cables and other microwave components and by taking greater care in fabrication. Modulation loss is suffered when not all of the transmitted energy can be usefully applied to send the information signal itself, but some of the energy must be expended to send a carrier frequency, a synchronizing signal, or similar signals.

Electronic equipment, like any manufactured item, seldom produces the exact performance specified; instead, the performance may be better or worse within certain tolerances. It is of importance that these tolerances be as small as possible since reliable communications can be guaranteed only if sufficient excess power is provided to overcome the negative (unfavorable) tolerances. Engineering opinion differs somewhat in choosing the method to account for the tolerances. The most optimistic approach is to assume that the nominal performance value will be achieved and to ignore the tolerances. Somewhat more conservative is the practice of taking the root-mean-square value of the tolerances. The approach that has been found realistic for this type of space communications during the last few years is to take the sum of the negative tolerances and to require sufficient system capability to overcome this sum.

For the given spacecraft and Earth receiving station in Table 1, the system performance in 1963 is a 27-db signal-to-noise ratio in a bandwidth of 15 kc/s. If this bandwidth were used by a single-sideband (SSB) modulation system to produce 525 $\times$ 525 element television at a video signal-to-noise ratio of 27 db, one frame would be sent every 2.5 sec. As will be seen later, the use of frequency modulation could increase this frame rate by more than five.

Table 1. Moon-to-Earth television

Parameter	1963	1968
Spacecraft		
RF frequency, Mc/s	2295	2295
RF power, w	10	50
Antenna diameter, ft	4	4
Modulation losses, db	1	1
Equipment RF losses, db	2	1
Earth receiving station		
Antenna diameter, ft	85	210
Effective noise temperature, °K	200	150
Space loss, db	212	212
Equipment RF losses, db	2	1
Sum of negative tolerances, db	4	3
System performance		
Bandwidth for S/N of 27 db, kc/s	50	4000
TV (525 × 525 line), frames/sec	0.4	30[a]

[a]This frame rate is the U. S. commercial standard.

By 1968, it is predicted that system performance will increase to a signal-to-noise ratio of 27 db in a bandwidth of 4 Mc/s. Thus, 30 frames/sec of 525 $\times$ 525 element television, the standard United States commercial SSB television format and quality, could be transmitted directly from the Moon to the station on Earth. As it happens, this standard SSB transmission not only outperforms other modulation schemes when the available bandwidth is limited but also is more convenient for rebroadcast around the United States.

Table 2 is concerned with emergency voice communications from the Moon to the Earth. In this application, in order to maintain communications regardless of the attitude of the spacecraft, it is necessary to discard the efficient, 4-ft diameter, directional antenna on the spacecraft and instead to use a spacecraft antenna of very low directivity. It is characteristic of these low directivity antennas that their gain in certain directions may be significantly lower, by about 10 db, than the nominal gain. If the spacecraft has lost attitude control and is tumbling, the signal strength received at the Earth will thus vary by about a factor of 10. Since in emergency conditions it will be necessary to send telemetry as well as voice communications from the spacecraft, the modulation losses will be larger than for the television application. The Earth receiving station is assumed to be the best available.

The system performance of a 13-db signal-to-noise ratio in a 5-kc/s band corresponds to a medium grade voice when the spacecraft is at its most unfavorable attitude. High grade voice is available under better conditions. If there is no emergency, of course, the appropriate operational technique is to use the highly efficient directional antenna and the average 1963 equipment to produce excellent quality voice.

Table 3 considers the problem of emergency voice communications from the Earth to the Moon. The Table is largely self-explanatory . A fairly high transmitter power of 10,000 w is selected to permit the use of a 1963 ground antenna and a comparatively crude spacecraft receiver. System performance is quite acceptable, even for unfavorable spacecraft attitudes. If greater performance is desired, the use of a simple parametric amplifier in the spacecraft receiver can improve performance by a factor of 10, of course, if no emergency exists, by using the spacecraft directive antenna for receiving, a far better system performance would be produced than would ever be required. Indeed, sufficient system performance would then exist to send television from the Earth to the Moon, a possibility of more psychological than technical importance.

Table 2. Moon-to-Earth emergency voice communications

Parameter	Value
Spacecraft	
RF frequency, Mc/s	2295
RF power, w	10
Antenna gain, db	3
Uncertainty in antenna gain, db	10
Modulation losses, db	3
Equipment RF losses, db	2
Earth receiving station	
Antenna diameter, ft	210
Effective noise temperature, °K	150
Space loss, db	212
Equipment RF losses, db	1
Sum of negative tolerances, db	3
System performance	
Bandwidth for S/N of 13 db (satisfactory grade voice), kc/s	5

Table 3. Earth-to-Moon emergency voice communications

Parameter	Value
Spacecraft	
Antenna gain, db	3
Uncertainty in antenna gain, db	10
Receiver noise temperature, °K	6,000
Equipment RF losses, db	2
Sum of negative tolerances, db	3
Space loss, db	211
Earth transmitting station	
Antenna diameter, ft	85
Transmitter RF power, w	10,000
RF frequency, Mc/s	2,113
Equipment RF losses, db	3
Modulation loss, db	3
System performance	
Bandwidth for S/N of 18 db (medium grade voice), kc/s	5

Figure 2 is a sketch of the communication problem of a lunar station on the far side of the Moon wishing to communicate with the Earth. One possible solution (shown in Fig. 2) is a set of five, equally spaced, lunar communication satellites that communicate both with the lunar station and with the Earth.[2] It is evident from the Figure that the minimum number of such satellites is five if continuous communications between the lunar station and the Earth are desired. The orbital radius should be somewhat more than three times the Moon's radius. Two of the communication satellites will be in communication position much of the time, providing a built-in redundancy for part of the time. More satellites would be required if the satellites are not equally spaced but are allowed to drift with respect to each other. The communication link between the Earth and the lunar communication satellite would be similar in design to one of the Moon-to-Earth communication links discussed previously. It would be desirable if an antenna could be used with directivity toward the Earth, but this may conflict with satellite simplicity and with the greater desirability of keeping a fairly broad-beamed antenna directed at the Moon. The beamwidth of the Moon-directed antenna should be about 40 deg, corresponding to an antenna gain of about 13 db. If it is not possible to use such a directive antenna, the equivalent antenna gain must be provided by the lunar station antenna.

The lunar station proves to be a remarkably simple set of equipment. Using a communication frequency of about 400 Mc/s, a receiving system temperature of about 600°K, helical antennas of about 2 ft in size, antenna beamwidths of 90 deg, and transmitter powers of only 5 w produces a system performance of a 15-db signal-to-noise ratio in a 5-kc/s bandwidth (medium grade voice). The 90-deg beamwidth of the antennas means that little or no tracking of the communication satellites is required at the lunar station. If an additional 13-db gain antenna must be provided by the ground station (see above), the ground station beamwidth narrows to 20 deg and the antenna size increases to 9 ft: coarse tracking of the communication satellite is then required. Alternatively, receivers more sensitive by a factor or two could be used with transmitters of ten times more power. If none of these alternatives were acceptable, the lunar communication satellite system could still provide excellent quality teletype and telemetry.

[2]Another, somewhat more complicated, solution uses a lunar satellite near the libration point, about 40,000 mi beyond the Moon from the Earth, as a relay. In performance and technical sophistication, such a satellite closely resembles satellites in synchronous orbits around the Earth. The choice of a solution is less important for the purposes of this Memorandum than is the fact that several alternative solutions are conceivable. For a discussion of libration points, see the Seifert reference, pp. 7-24.

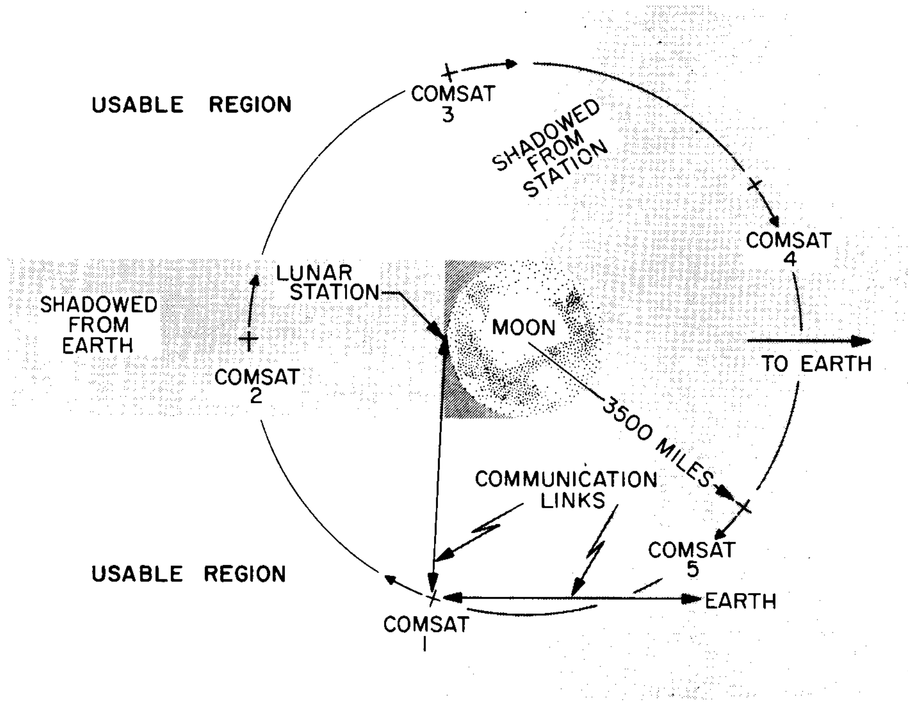

Fig. 2. Communications from the far side of the Moon

III. COMMUNICATIONS BETWEEN POINTS ON THE SURFACE OF THE MOON

Communications between arbitrary[3] points on the lunar surface are predicted to be considerably more difficult than those between similarly spaced points on the surface of the Earth. Because the Moon is smaller in diameter than the Earth by a factor of four, the local horizons are half as far away. To see the same distance, the observer must be four times as far above the lunar surface as above the Earth's surface. In addition, radar measurements from the Earth indicate that the surface of the Moon is considerably more absorbing of RF energy than is a typical surface on the Earth. A somewhat unfavorable dielectric constant also acts to make propagation of a wave along the lunar surface relatively difficult. Even the lunar ionosphere, if there is one, is unfavorable. Unlike the Earth's ionosphere, which has a maximum ionization, and consequently reflecting, "layer" about 60 mi above the Earth's surface, the lunar ionosphere has maximum ionization at the surface of the Moon. Consequently, the Moon's ionosphere, instead of reflecting radio waves back to the lunar surface, acts to deflect them away into space.

Figure 3 is a sketch of the problem of surface-to-surface communications on the Moon.

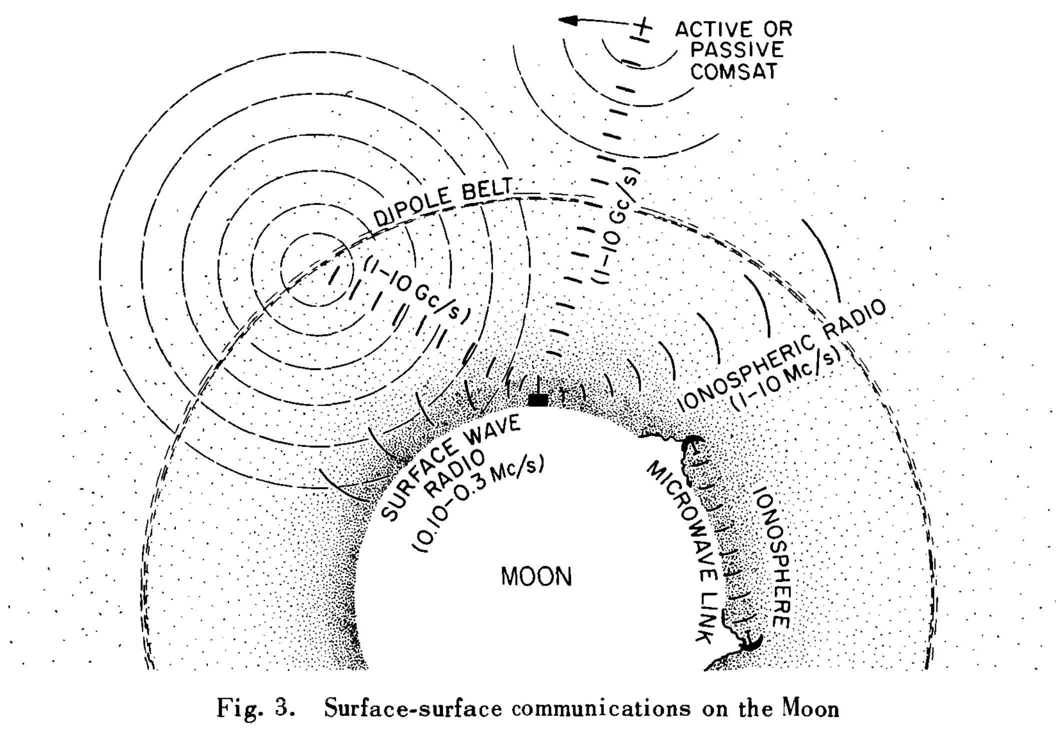

Fig. 3. Surface-surface communications on the Moon

[3]If all points of interest are on the Earth side of the Moon, talking via the Earth is accomplished fairly easily by using the types of links described earlier.

Table 4 is a comparison of various techniques for sending a specified quality signal (15 db S/N in 5 kc/s) from one point on the lunar surface to another. As can be seen from the Table, the surface range of ionospheric radio is unacceptably short. The surface wave radio has a somewhat greater range but requires a structure of several hundred feet and a transmitter power of 500 w to reach only 60 mi. The microwave link is more reasonable in antenna size and transmitter power, but it is limited to line of sight. Assuming that parabolas could be established on hills 300 ft high with respect to the rest of the terrain, it would be possible to see barely 20 mi between hills or 10 mi to the flat terrain. Furthermore, the microwave antenna beamwidth of only 4 deg would preclude roving parties from communicating easily with a microwave station.

To span any major distance along the lunar surface, it therefore appears necessary to use satellites. A comparison of *Echo* balloons, dipole belts, and active communication satellites shows a pronounced advantage for the active communication satellite. Because such satellites, uniquely among the techniques compared here, can also communicate with the Earth, such a solution would appear to have a considerable operational advantage over the others.

Table 4. A comparison of surface lunar voice links

	Ionospheric radio	Surface wave radio	Microwave link	Via *Echo* balloon	Via dipole belt	Via (5) comsats
S/N in 5 kc/s, db	15	15	15	15	15	15
Surface range, mi	<10	60	20	2,500	2,500	2,500[a]
Approximate frequency, Mc/s	3	0.3	6,000	6,000	8,000	400
Receiving temperature, °K	10^5	10^7	600	300	300	600
Antenna type	Rhombic	Vertical and horizontal wires	Parabolas on 300-ft hills	Parabolas	Parabolas	Helices
Antenna beamwidth, deg	40	40	4	0.4	0.3	90
Antenna size, ft	75	200	3	30	30	2
Transmitter power, w	10	500	1	10,000	10,000	5

[a]The range includes nearly the whole lunar surface if Earth-comsat links are also used.

IV. MODULATION TECHNIQUES

It is a well-known phenomenon in communications that the signal-to-noise ratio S/N at the output of a communication system can be increased if more bandwidth is used in the RF link. This result appears to be erroneous in a way, because it has been stated previously that the amount of noise power at the receiver terminals increases proportionately with the bandwidth. However, there is a counteracting effect that more than overcomes the additional noise power. This effect, essentially, is due to the increased distinctiveness or uniqueness of the signal waveform (in contrast to the irregular waveform of noise) that is produced by the use of wider bandwidths. Needless to say, the right kind of receiver, tailored to extracting the particular waveform, must be used or the advantage of the expanded bandwidth will be lost. Roughly speaking, for the common modulation systems, the S/N improvement ratio is about the same in practice as the RF bandwidth ratio.

Reading through the literature, one finds as many ways of comparing modulation systems as there are modulation systems themselves. Indeed, it almost appears that, provided the appropriate receiver is used for each modulation technique, any given modulation system can be shown to be superior to all others!

The reason for this state of affairs is that modulation system performance is strongly influenced by such side constraints as assumed threshold point, allowable RF bandwidth, desired signal-to-noise ratio improvement, uncertainties or randomness in the communication link parameters, and so forth. Stated in another way, the nature of the application strongly influences the choice of modulation system.

It would be fortunate indeed if there were analytical techniques that would permit a synthesis of the best modulation technique for a given application. Instead, increasingly better analytical techniques exist for describing the performance of any given modulation system for a given application, and a comparison must be made among all the analyzed techniques in order to make the choice. Such an analytical technique therefore has the obvious disadvantage that the best modulation technique may have been forgotten by the analyst.

With this disclaimer, a comparison will be made of the TV frame rates that can be achieved by four different modulation systems for the same quality picture and the same basic communication equipment.

The previous discussions have shown that it is the purpose of the communication system (excluding the modulation subsystem) to produce as high a signal power and as low a noise spectral density as possible, that is, to produce a large S_{RF}/Φ. In comparing modulation systems, we will assume that the same basic communication equipment (the same S_{RF}/Φ) is available to all. The available equipment, of course, depends upon the state-of-the-art and operational conditions.

Modulation systems use S_{RF}/Φ in various ways. Single sideband uses a minimum RF bandwidth transmission, just enough to reproduce the original information rate. Simple detection is used such that the output video signal-to-noise ratio is the same as the RF signal-to-noise ratio. In other words,

$$(S/N)_{\text{video}} = (S/N)_{RF} = \frac{S_{RF}}{\Phi} \frac{1}{B_{RF}} \tag{3}$$

(single sideband)

Frequency modulation converts the original amplitude information to frequency, making a more distinctive signal waveform but requiring more bandwidth, and then uses nonlinear detection to extract preferentially the signal from noise. In the frequency-modulation case, the output signal-to-noise ratio is given by the following proportionality:

$$(S/N)_{\text{video}} \sim m^2 \frac{S_{RF}}{\Phi} \tag{4}$$

(frequency modulation)

where the modulation index m is a measure of the bandwidth expansion compared with SSB.

In more elaborately coded systems, the output signal-to-noise ratio can be shown to be exponentially related to S_{RF}/Φ as follows:

$$(S/N)_{\text{video}} \sim \exp \frac{S_{RF}}{\Phi f_0} \tag{5}$$

(coded modulation)

where f_0 is a constant determined by the maximum information rate and the particular coding scheme.

Two constraints act to limit the performance of modulation systems for lunar television: the threshold phenomenon and an RF bandwidth limitation.

Figure 4 is a sketch of the threshold phenomenon. Techniques that, as compared with the direct SSB technique, improve the output signal-to-noise ratio all have the characteristic that, below a certain level of input signal-to-noise ratio, their performance degenerates very rapidly. The degeneration is so rapid that performance drops below that of the simple SSB system. The more sophisticated the modulation system, the more abrupt the threshold. Operation near threshold carries with it the risk that, should the input signal-to-noise ratio decrease for any reason, communication is lost. This characteristic is well known to users of FM radio in automobiles who find that, within a space of a few driving miles away from an FM station, reception can change from very good to almost nonexistent. Conservative design practice thus avoids operation too close to threshold. On the other hand, the closer the operation is to threshold, the greater the relative improvement of the modulated system over the simpler systems. For example, we have seen in FM reception that the output signal-to-noise ratio increases as the square of the modulation index (Eq. 4). But, it can also be shown that[4]

$$m^2(m + 1) \sim (S/N)_{RF}^{-1} \tag{6}$$

and thus the maximum m (peak performance) is achieved at, and is limited by, the minimum threshold $(S/N)_{RF}$.

It is fairly easily shown that simple transmission of the amplitude of a signal is less efficient than coding this amplitude into a binary number and transmitting the number instead. For example, a signal whose amplitude can vary from 1 to 32 in a space of Δt sec can be coded into a series of binary numbers of 5 pulses each, where each 5-pulse number is sent in Δt sec. Of course, the binary number transmission occupies five times the bandwidth of the simpler system. However, the binary waveform is more distinctive in that the binary system requires a smaller $(S/N)_{RF}$ in its larger RF bandwidth to produce output signals of the same accuracy. In the example given here, the additional noise in the wider bandwidth binary system is more than compensated for by about a factor of five. This particular binary system is also known as pulse coded modulation (PCM). A still different coding scheme, orthogonal FM, sends the quantized levels of the original signal as an equivalent number of separate frequencies.

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[4]See Part III of the Appendix.

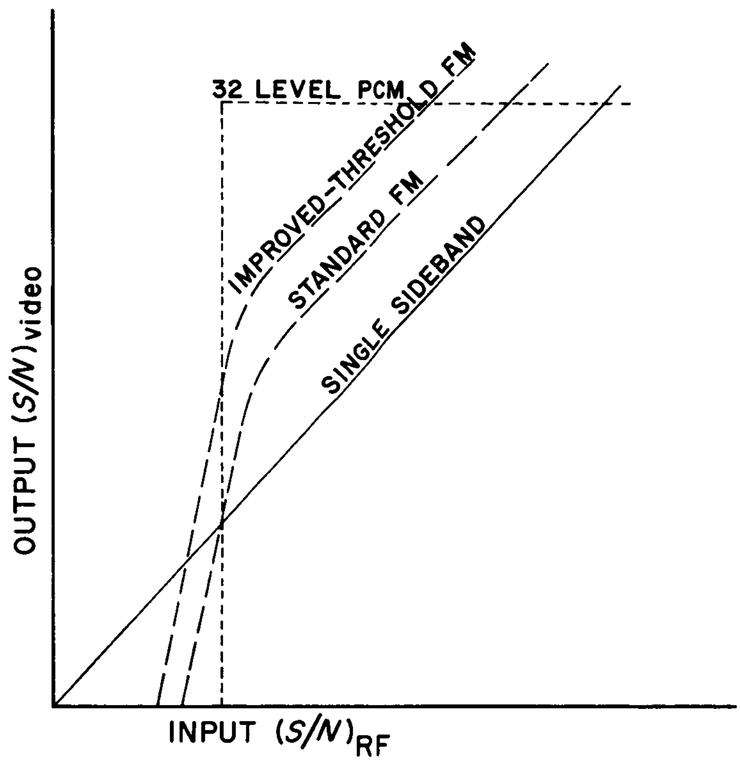

Fig. 4. Sketch of the threshold phenomenon

However, in all such systems, the quantizing process introduces a quantization error—the amplitude resolution in the output signal can never be better than one level, or 1:32 in the previous example. This limit on the output S/N holds even when the $(S/N)_{RF}$ is far greater than threshold. This performance-limiting effect is shown in Fig. 4.

The second major constraint on modulation systems is the bandwidth limitation. It is not possible in today's world of the crowded frequency spectrum to occupy bandwidth without limit. As an increasing amount of S_{RF}/Φ is made available by better equipment, the usual tendency is to try to exploit the increase by increasing the information (frame) rate. This increase of necessity increases the RF bandwidth of whatever modulation system is being used. The most sophisticated systems, generally speaking, require the greatest bandwidth and consequently are constrained first from further frame-rate increases. The minimum bandwidth system, SSB, is constrained last.

As a result, coded systems are most worthwhile for low frame rates, giving way to simpler systems as the required video bandwidth approaches the available RF bandwidth. When the required video bandwidth equals the RF bandwidth, SSB excels. Strictly speaking, it is possible to "code" the input signal in such a way as to remove internal redundancy in the signal itself, reducing the video and RF bandwidths required to less than those of "uncoded" SSB. But, to date, such coding has seen little use in space communications and is best considered as a future possibility for special signal types.

This highly qualitative discussion of modulation systems can be made much more quantitative. The Appendix contains the equations governing the performance of SSB, standard FM, improved-threshold FM, orthogonal (partially coded) FM, and phase modulation (PM).

In the comparison of other modulated systems with SSB, however, a peculiarity of SSB works to its disadvantage. Because of the nonconstant waveform envelope, SSB requires linear transmitters capable of low-distortion transmission of peak powers many times the average power. Because the other systems considered here all have constant output powers, SSB may require the use of less efficient transmitting devices with a resultant penalty in system performance. Should the SSB system prove unacceptably inefficient, a close cousin of SSB, low-deviation PM, might be used. However, efficient transmission requires the use of a 1-rad phase-modulation index that results in an RF bandwidth about four times that of SSB. If PM efficiency is sacrificed, the RF bandwidth can be reduced somewhat; for efficiencies of 50% or less, the RF bandwidth is twice that of SSB.

V. A COMPARISON OF MODULATION TECHNIQUES FOR LUNAR TELEVISION

The calculations for a lunar TV link using SSB, standard FM, improved-threshold FM, orthogonal FM, and phase modulation are given in the Appendix.

Figure 5 shows the results of the calculations. The bandwidth limitations used in Fig. 5 are typical of those expected in the 1 to 3 Gc/s region. Assuming contiguous allocations, a 3-Mc bandwidth would, therefore, use one channel, a 6-Mc bandwidth would use two contiguous channels, and a 9-Mc bandwidth would use three. For S_{RF}/Φ less than about 10^7, orthogonal FM gives the greatest frame rate. However, orthogonal FM requires large bandwidths in order to achieve its superior performance, and when allowable bandwidth limits are reached, further increases in frame rate are precluded.

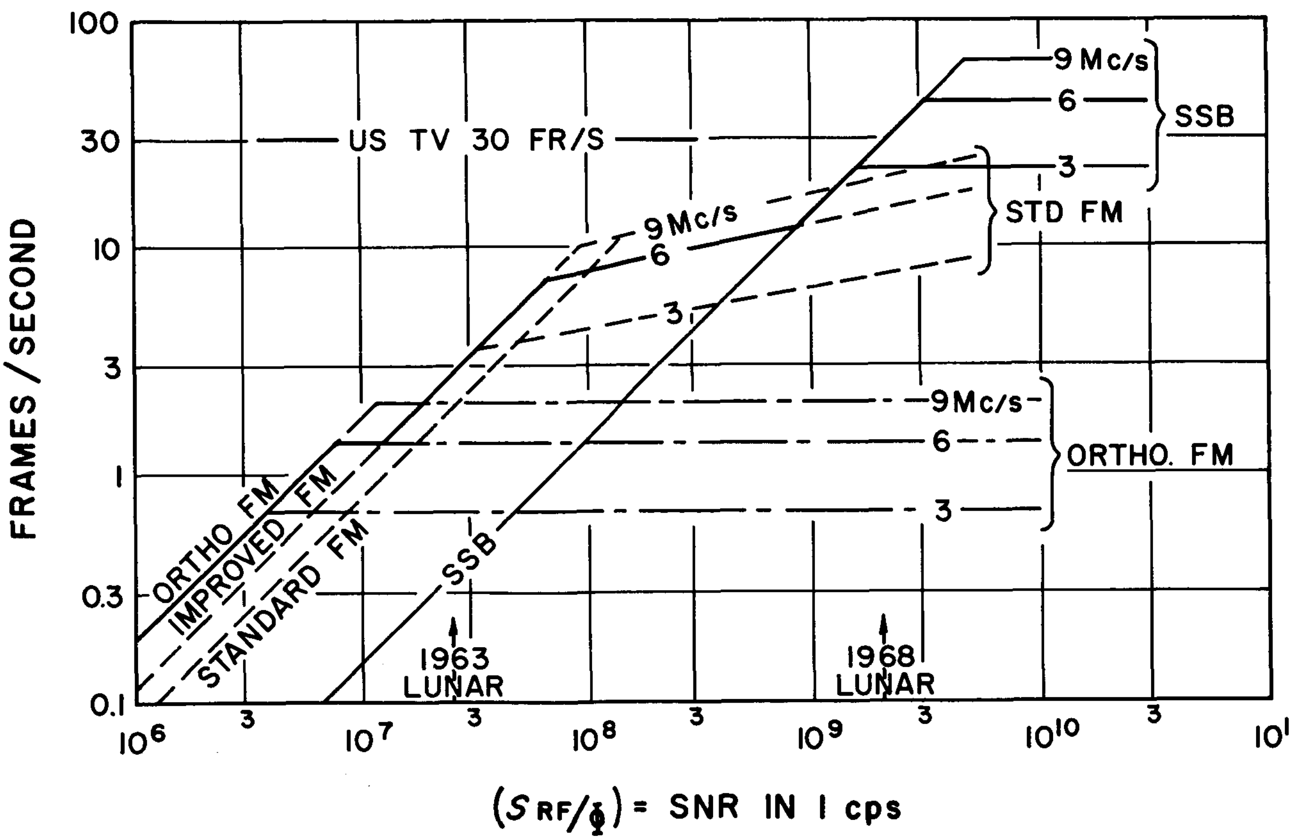

Fig. 5. Lunar television modulation systems for video S/N of 27 db

For S_{RF}/Φ between 10^7 and 10^8, a range including the equipment performance expected in 1963, improved-threshold FM is best until it, too, reaches the bandwidth limitation.

For S_{RF}/Φ between 10^8 and 10^9, the best system shown is standard FM using a fairly small modulation index (less than two) that decreases with increasing S_{RF}/Φ and frame rate in order to keep within the RF bandwidth limits. It is worth noting that, in this region of S_{RF}/Φ, the frame-rate improvement is limited by bandwidth constraints to less than a factor of two for a communication equipment performance improvement of more than ten.

For S_{RF}/Φ greater than 10^9, as qualified by the previous discussion, SSB is the preferred system with the maximum frame rates being largely determined by bandwidth limitations. This region of S_{RF}/Φ includes the expected lunar communication performance in 1968.

VI. USE OF OPTICAL FREQUENCIES

Winking lights have been used for optical communication of information for centuries. However, the light sources, whether sunlight or light bulbs, produced their visible energy spread over very great bandwidths (thousands of megacycles). These communication links were also easily stopped by fog or rain. The achievable beamwidths were seldom smaller than about a degree. Such links were thus vulnerable to background light (noise) and were both inefficient and limited in range compared with radio links.

Optical communication links have recently acquired an advantage with the development of the laser, which provides a very narrow bandwidth source, promises the development of a coherent receiver similar to the best RF receivers, and generates extremely directive beams.

Fortunately, for comparison purposes, optical communication links can be treated in almost the same way as radio links. Optical links have powers, antenna gains, losses, etc. Optical temperatures differ from radio temperatures in that they are due to quantized photon effects instead of molecular noise, but they produce a comparable effect in the communication link.

Table 5 compares optical and radio lunar communications. In this comparison, coherent detection, phaselock elimination of doppler shift, and precise aiming of the transmitter at the receiver are all assumed, although none of these have yet been demonstrated for optical links. The spacecraft power in watts is determined by the available input power and the efficiencies of the optical and radio transmitters. The first advantage goes to the more efficient radio transmitters by a factor of 20 db at present, although this advantage may well diminish with optical transmitter development. The transmitting-antenna beamwidth for the optical system is far narrower than for the radio system; consequently, the equivalent antenna gain gives the first marked advantage to the optical system. However, optical frequencies are far higher than radio frequencies so that the space loss, as defined earlier, is considerably higher; the cumulative advantage returns to the radio system. However, the receiving antenna for an optical system is again highly directional compared with a radio system such that the optical system is a few db better than the radio system at this point in the comparison. Two factors now enter that seriously degrade the optical system: the receiving noise temperature and the detector efficiency. As a result of these two factors, the advantage again goes to the radio system.

Atmospheric attenuation due to fog and rainfall can be so great for an optical system that further comparison is useless if highly reliable communication to a specified point on the Earth is demanded. One

Table 5. A comparison of optical and radio lunar communications

Parameter	Optical value	Radio value	Cumulative advantage to optical, db
Spacecraft power, w	0.10	10	−20
Transmitting antenna beamwidth	25 μ rad	5 deg	
Transmitting antenna gain, db	103	26	+57
Transmitting wavelength, cm	0.7×10^{-4}	13	
Space loss, db	−318	−212	−49
Receiving antenna beamwidth	25 μ rad	0.35 deg (85 ft)	
Receiving antenna gain, db	103	52	+ 2
Receiving noise temp, °K	20,000	150	−19
Detector efficiency	0.01	1	−39
Atmospheric attenuation, db	1 to > 60[a]	1	−39
Improvement in radio system			
Larger spacecraft and ground antennas (16 db)			−55
Improvements in optical system			
Larger receiving area (42 db) partly offset by atmosphere-produced incoherency (−10 to −20 db)			−23 to −33
Improved detector efficiency (10 db)			−13 to −23
Improved transmitter efficiency (17 db)			+ 4 to −6

[a]This attenuation might be eliminated by using widely dispersed receiving stations.

way, perhaps, to achieve reliability of optical communications (at least to the Earth as a whole) is to use widely dispersed receiving stations for the optical system. Admittedly, this multiplicity of stations markedly increases the cost of the system and presents a problem in relaying the communications to the specified point on the Earth.

Looking further into the future, we might expect improvements in both systems to diminish the relative advantage of the radio system over the optical system, although it is difficult to predict a marked ascendancy of the optical approach for the applications considered so far. In any case, the optical link would be considerably more difficult to use operationally. Since the spot size on the Earth of the optical beam transmitted from the Moon is only 6 mi in diameter, the lunar transmitter would have to track the moving Earth station. A pointing accuracy of 5 μ rad would be required of the spacecraft-transmitter antenna. (The reasonably precise, mechanical pointing systems of today are poorer than this by a factor of several hundred.) A doppler shift of over 400 Mc would be expected on the optical link because of the motion of the Earth station caused by Earth rotation. The optical beam would be refracted by the atmosphere so that, in order to maintain communications, continuously corrective techniques would have to be applied at both the transmitting and receiving antennas. It is also evident that optical links are noncompetitive whenever omnidirectionality or broad beamwidths are required of the transmitter or the receiver for operational reasons.

VII. CONCLUSIONS

1. Communication to and from the Moon is practical with data rates and quality comparable to those between points on the Earth.

2. Communication from the far side of the Moon is probably best achieved with five or more lunar satellites in a lunar orbit of 3500 mi or greater.

3. Communication along the lunar surface for distances of more than about 10 mi is probably easiest via a lunar satellite, particularly if a link also exists between the lunar satellite and the Earth.

4. In 1963, a standard FM system is probably best for a maximum frame rate from the Moon; by 1968, SSB may be better; however, the choice of modulation technique is strongly influenced by operational constraints.

5. Optical frequencies are presently noncompetitive for lunar communications and will probably remain so, with the possible exception of applications requiring extreme directivity and very small antennas.

NOMENCLATURE

A_R	receiving antenna area
B_c	allowable channel bandwidth, cps
B_{RF}	radio-frequency bandwidth, cps
B_{video}	base or TV information bandwidth, cps
$\overset{\circ}{F}$	frame rate for TV pictures, frames/sec
f_m	maximum modulating frequency, cps
G_R	receiving antenna gain
G_T	transmitting antenna gain
k	Boltzman's constant (1.38×10^{-23} w/cps/°K)
L	number of levels chosen for orthogonal FM quantization
m	FM modulation index, dimensionless
N_{RF}	effective noise power at the radio frequency receiver terminals, including noise contributions of receiver, w
P_E	probability of error for detector in orthogonal FM
P_T	transmitted power
R	communication distance in the same units as λ
S_{RF}	received signal power at the radio frequency, w
$(S/N)_{\mathrm{RF}}$	signal-to-noise ratio at the radio frequency
T	temperature, °K
T_0	transmitting period per TV element for orthogonal FM
Th	threshold
λ	wave length
$\lambda^2/(4\pi R)^2$	the space loss (so defined for this discussion)
Φ	noise spectral density, w/cps
ϕ	phase-modulation deviation, rad
ϕ^2	mean-square phase-modulation deviation, rad^2

APPENDIX A

Governing Equations and Uses of Modulation Systems

I. GOVERNING EQUATIONS FOR SINGLE SIDEBAND

$$\left(\frac{S}{N}\right)_{\text{video}} = \frac{S_{\text{RF}}}{B_{\text{RF}}\,\Phi} = \frac{S_{\text{RF}}}{B_{\text{video}}\,\Phi}$$

$$\overset{\circ}{F} = \left(\frac{2}{\begin{array}{c}\text{no. of elements}\\ \text{per frame}\end{array}}\right) B_{\text{video}} \text{ frames/sec}$$

$$= \left(\frac{2}{\begin{array}{c}\text{no. of elements}\\ \text{per frame}\end{array}}\right)\left(\frac{N}{S}\right)_{\text{video}}\left(\frac{S_{\text{RF}}}{\Phi}\right) \text{ frames/sec}$$

For the $(S/N)_{\text{video}}$ of interest, SSB does not reach a threshold. The maximum available bandwidth B_c is reached when

$$B_{\text{RF}} = B_c = B_{\text{video}}$$

$$= \left(\frac{\begin{array}{c}\text{no. of elements}\\ \text{per frame}\end{array}}{2}\right) \overset{\circ}{F} \text{ cycles/sec}$$

and, consequently,

$$\overset{\circ}{F}_{\max} = \left(\frac{2B_c}{\begin{array}{c}\text{no. of elements}\\ \text{per frame}\end{array}}\right) \text{ frames/sec}$$

II. USE OF SINGLE SIDEBAND FOR LUNAR TELEVISION

For a specified TV picture of 525 × 525 elements per frame and a $(S/N)_{\mathrm{video}}$ of 500 (i.e., 27 db), the frame rate is given by

$$\overset{\circ}{F} = \left(\frac{2}{525 \times 525}\right)\left(\frac{1}{500}\right)\left(\frac{S_{\mathrm{RF}}}{\Phi}\right) = 1.45 \times 10^{-8}\left(\frac{S_{\mathrm{RF}}}{\Phi}\right) \text{ frames/sec}$$

up to a maximum frame rate controlled by typical allowable bandwidths of 3, 6, and 9 Mc/s, i.e., up to frame rates of

$$\overset{\circ}{F}_{\mathrm{max}} = \frac{2(3 \text{ or } 6 \text{ or } 9) \times 10^{6}}{525 \times 525} = 22,\ 44, \text{ or } 66 \text{ frames/sec}$$

III. GOVERNING EQUATIONS FOR STANDARD FM

$$\left(\frac{S}{N}\right)_{\mathrm{video}} = 3m^{2}\left(\frac{S_{\mathrm{RF}}}{2\Phi f_{\mathrm{m}}}\right)$$

$$\overset{\circ}{F} = \left(\frac{2f_{m}}{\text{no. of elements per frame}}\right)$$

$$= \left(\frac{2}{\text{no. of elements per frame}}\right)\left(\frac{N}{S}\right)_{\mathrm{video}}\left(\frac{S_{\mathrm{RF}}}{\Phi}\right)\left(\frac{3m^{2}}{2}\right) \text{ frames/sec}$$

Threshold is determined by

$$\left(\frac{S_{RF}}{N}\right)_{Th} = 16 = \frac{S_{RF}}{B_{RF}} = \left(\frac{S_{RF}}{\Phi}\right)\frac{1}{2(m+1)f_m}$$

and, consequently, by

$$m^2(m+1) = \frac{\left(\frac{S}{N}\right)_{\text{video}}}{3\left(\frac{S_{RF}}{N}\right)_{Th}} = \frac{\left(\frac{S}{N}\right)_{\text{video}}}{48}$$

The maximum available bandwidth B_c is reached when

$$\begin{aligned} B_{RF} = B_c &= 2(m+1)f_m \\ &= (m+1)\begin{pmatrix}\text{no. of elements} \\ \text{per frame}\end{pmatrix}\overset{\circ}{F} \text{ cycles/sec} \end{aligned}$$

and, consequently,

$$\overset{\circ}{F}_{max} = \frac{B_c}{\begin{pmatrix}\text{no. of elements} \\ \text{per frame}\end{pmatrix}(m+1)}$$

IV. USE OF STANDARD FM FOR LUNAR TELEVISION

For a specified TV picture of 525 × 525 elements per frame and a $(S/N)_{\text{video}}$ of 500, the frame rate is given by

$$\overset{\circ}{F} = \left(\frac{2}{525 \times 525}\right)\left(\frac{1}{500}\right)(1.5\,m^2)\left(\frac{S_{RF}}{\Phi}\right) = 2.18 \times 10^{-8}\,m^2\left(\frac{S_{RF}}{\Phi}\right) \text{ frames/sec}$$

The best frame rate is thus achieved for the largest m that is reached at threshold, i.e., at $m^2(m + 1) = 500/48$ or $m = 1.9$. Thus,

$$\overset{\circ}{F} = (2.18)(1.9)^2 \times 10^{-8} \left(\frac{S_{RF}}{\Phi}\right)$$

$$= 7.85 \times 10^{-8} \left(\frac{S_{RF}}{\Phi}\right) \text{ frames/sec}$$

up to a frame rate controlled by typical allowable bandwidths of 3, 6, or 9 Mc/s, i.e., up to frame rates of

$$\overset{\circ}{F}_{max} = \frac{(3 \text{ or } 6 \text{ or } 9) \times 10^6}{(525 \times 525)(1.9 + 1)} = 3.75, 7.5, \text{ or } 11.3 \text{ frames/sec}$$

Greater frame rates than these can be achieved by operating less efficiently, i.e., by using a smaller m and consequently more (S_{RF}/Φ).

1. For $m = 1.5$, the corresponding $\overset{\circ}{F}_{max}$ are 4.35, 8.7, and 13 frames/sec at (S_{RF}/Φ) of 0.9×10^8, 1.77×10^8, and 2.65×10^8, respectively.

2. For $m = 1.0$, the corresponding $\overset{\circ}{F}_{max}$ are 5.44, 10.9, and 16.3 frames/sec at (S_{RF}/Φ) of 2.5×10^8, 5×10^8, and 7.5×10^8, respectively.

3. As m approaches zero and (S_{RF}/Φ) goes to infinity, $\overset{\circ}{F}_{max}$ approaches 11, 22, and 33 frames/sec for the 3, 6, and 9 Mc/s bandwidth limits.

V. GOVERNING EQUATIONS FOR IMPROVED-THRESHOLD FM

From inspection of the standard FM performance, it is evident that better performance would be achieved with larger m, which in turn demands a smaller $(S_{RF}/N)_{Th}$. There are various ways of mechanizing the reduced threshold (such as FM with feedback or phase-lock loop detection). The threshold equations are somewhat different schemes, but for simplicity in the discussion it will be assumed that an $(S_{RF}/N)_{Th} = 10$ is achieved, yielding an $m = 2.25$. Then, for lunar TV,

$$\overset{\circ}{F} = 11 \times 10^{-8} \left(\frac{S_{RF}}{\Phi} \right) \text{frames/sec}$$

up to a frame rate controlled by allowable bandwidths of 3, 6, or 9 Mc/s, i.e., up to frame rates of

$$\overset{\circ}{F}_{max} = \frac{(3 \text{ or } 6 \text{ or } 9) \times 10^6}{(525 \times 525)(2.25 + 1)}$$

$$= 3.35, 6.7, \text{ or } 10 \text{ frames/sec}$$

Greater frame rates, as in standard FM, are achieved only by less efficient operation. The performance of improved-threshold FM equates to that of standard FM when the modulation indices are equal.

VI. GOVERNING EQUATIONS FOR ORTHOGONAL FM

A recent innovation[A-1] in FM has been the incorporation of quantization and coding, producing an FM performance much like that of PCM and reducing the equivalent FM threshold "approximately to the extreme position." Each TV picture element is first quantized into L levels determined by the desired $(S/N)_{video}$. The picture element is transmitted by selecting the appropriate one of L frequencies and transmitting it for T_0 sec. If the L frequencies are all phase coherent, they may be separated by $(2T_0)^{-1}$ cps. The receiver consists of L correlation detectors (one for each frequency) followed by a maximum likelihood (best) detector. To keep quantization noise reasonably small, $L^2 > 1.1\ (S/N)_{video}$. To include sufficient RF spectrum space to account for the spectrum of frequencies transmitted for $(2T_0)^{-1}$ sec, the RF bandwidth should be

$$B_{RF} \approx \frac{L + 8}{2T_0}$$

[A-1]See the Battail reference and the second Viterbi reference in the Bibliography.

The $(S/N)_{\text{video}}$ achieved by such a system is given by

$$\left(\frac{S}{N}\right)_{\text{video}} = \frac{L^2}{1 + 2P_E(L^2 + L)}$$

where P_E is the probability of a maximum likelihood detector making an error[A-2]. For reasonable lunar TV performance, use $P_E \lesssim 10^{-4}$, for which $(S_{RF}T_0/\Phi) \geq 20$. The frame rate is

$$\overset{\circ}{F} = \frac{1}{T_0\begin{pmatrix}\text{no. of elements}\\ \text{per frame}\end{pmatrix}} \text{ frames/sec}$$

$$= \frac{1}{20\begin{pmatrix}\text{no. of elements}\\ \text{per frame}\end{pmatrix}} \left(\frac{S_{RF}}{\Phi}\right) \text{ frames/sec}$$

up to a frame rate controlled by the allowable bandwidth B_c so that

$$\overset{\circ}{F}_{\max} = \frac{2B_c}{\begin{pmatrix}\text{no. of elements}\\ \text{per frame}\end{pmatrix}(L + 8)}$$

Greater frame rates cannot be achieved without reducing L, which in turn increases the quantization noise level above the acceptable limit determined by the desired $(S/N)_{\text{video}}$.

Alternative selections come to mind (sending two frequencies at once instead of only one, thus requiring one-fourth as great an L but a greater S_{RF}/Φ) that would produce a somewhat higher frame rate less efficiently, much as in standard FM. In the limit as L goes to zero, S_{RF}/Φ goes to infinity and $F_{\max}$ goes to $0.25\, B_c$ (no. of elements per frame)$^{-1}$.

[A-2] A plot of P_E is found in Fig. 6 of the second Viterbi article.

VII. USE OF ORTHOGONAL FM FOR LUNAR TELEVISION

For a specified TV picture of 525 × 525 elements per frame and a $(S/N)_{video}$ of 500, $L = 24$,

$$\mathring{F} = \frac{1}{20(525 \times 525)} \left(\frac{S_{RF}}{\Phi} \right) \text{ frames/sec}$$

$$= 18.3 \times 10^{-8} \left(\frac{S_{RF}}{\Phi} \right) \text{ frames/sec}$$

up to a frame rate controlled by the allowable bandwidths of 3, 6, or 9 Mc/s, i.e., up to frame rates of

$$\mathring{F}_{max} = \frac{2(3 \text{ or } 6 \text{ or } 9) \times 10^6}{(525 \times 525)(24 + 8)}$$

$$= 0.68,\ 1.36,\ \text{or } 2.04 \text{ frames/sec}$$

Since greater frame rates cannot be achieved without a considerable change in mechanization, they will not be considered.

VIII. GOVERNING EQUATIONS FOR PHASE MODULATION WITH PHASE-LOCKED RECEIVER

$$\left(\frac{S}{N} \right)_{video} = \frac{\overline{\phi^2}}{B_{video}} \left(\frac{S_{RF}}{\Phi} \right)$$

in which $\overline{\phi^2}$ is the mean-square phase deviation produced by the modulating signal. For $\overline{\phi^2}$ less than one and for $(S/N)_{video}$ large, no threshold occurs. The RF bandwidth depends on $\overline{\phi^2}$ such that[A-3]

[A-3] *Modulation Theory*, H. S. Black, pp. 188-9.

$$B_{\mathrm{RF}} \simeq 4\, B_{\mathrm{video}} \qquad \text{for } \overline{\phi^2} = 1$$

$$B_{\mathrm{RF}} \simeq 2\, B_{\mathrm{video}} \qquad \text{for } \overline{\phi^2} = 1/2$$

IX. APPLICATION OF PHASE MODULATION TO LUNAR TELEVISION

Phase modulation with $\overline{\phi^2} = 1$ thus gives the same performance as SSB but requires four times the bandwidth. In Fig. 5, the $\overline{\phi^2} = 1$ PM curve would thus coincide with the SSB curve from low frame rates to 5.5 frames/sec at which the PM curve would level off for a 3-Mc/s band limit, to 11 frames/sec for 6 Mc/s, and 16.5 frames/sec for 9 Mc/s.

Phase modulation with $\overline{\phi^2} = 1/2$ gives one-half the performance of SSB (twice the S_{RF}/Φ is required for the same F) and requires two times the bandwidth. In Fig. 5, the $\overline{\phi^2} = 1$ PM curve thus lies parallel to the SSB curve, but lower by a factor of two in frame rate, and breaks horizontally at 11, 22, and 33 frames/sec for band limits of 3, 6, and 9 Mc/s, respectively. The U.S. standard 30-frame/sec TV can thus be sent by phase modulation using $\overline{\phi^2} = 1/2$, an RF bandwidth of 8 Mc/s, and an S_{RF}/Φ of 4×10^9.

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